

**RECONNAISSANCE INVESTIGATION
OF VOLATILE AND SEMIVOLATILE
ORGANIC COMPOUNDS IN THE
MEMPHIS AQUIFER AT ALAMO,
CROCKETT COUNTY,
TENNESSEE**

Prepared by the
U.S. GEOLOGICAL SURVEY



in cooperation with the
**TENNESSEE DEPARTMENT OF HEALTH AND ENVIRONMENT,
DIVISION OF SUPERFUND**

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Susan S. Hutson and Connor J. Haugh

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1992**

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CONVERSION FACTORS, VERTICAL DATUM, AND WELL-NUMBERING SYSTEM

<i>Multiply</i>	<i>By</i>	<i>To obtain</i>
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi ²)	2.590	square kilometer
gallon (gal)	3.785	liter
gallon per minute (gal/min)	0.06309	liter per second
gallons per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Temperature in degrees Fahrenheit (°F) can be converted to
degree Celsius (°C) as follows:

$$^{\circ}\text{C} = ^{\circ}\text{F} \times 0.5556(^{\circ}\text{F}-32)$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Well-numbering system: Wells are identified in the text of this report by an informal one-digit number and in table 3 by a formal number assigned in accordance with the U.S. Geological Survey's (USGS) well-numbering system. The well numbering system of the USGS is based on the grid system of latitude and longitude. The system provides the geographic location of the well and a unique 15-digit number for each site. The first 6 digits denote degrees, minutes, and seconds of latitude; the next 7 digits denote degrees, minutes, and seconds of longitude; and the last 2 digits (assigned sequentially) identify the wells within a 1-second grid.

Use of trade names, in this report, is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

RECONNAISSANCE INVESTIGATION OF VOLATILE AND SEMIVOLATILE ORGANIC COMPOUNDS IN THE MEMPHIS AQUIFER AT ALAMO, CROCKETT COUNTY, TENNESSEE

By Susan S. Hutson and Connor J. Haugh

ABSTRACT

Samples of ground water and soil gas were analyzed to study the occurrence of volatile and semivolatile organic compounds in the Memphis aquifer at Alamo in western Tennessee in 1989. At Alamo, the aquifer is locally unconfined. Four wells screened in the Memphis aquifer provided Alamo with 0.3 million gallons of water per day. Trichloroethylene (TCE), dichloroethylene, trichloroethane, and tetrachloroethylene were detected in water samples from two of the wells. In September 1989, the TCE concentration in a sample from well 1 was 45 micrograms per liter ($\mu\text{g/L}$); Tennessee's maximum contaminant level for TCE in drinking water is 5 $\mu\text{g/L}$. Concentrations of TCE in water from this well ranged from 40 to 113 $\mu\text{g/L}$ during 1988 and 1989. TCE concentration in water collected from well 2 in September 1989 was 0.7 $\mu\text{g/L}$. During 1988 and 1989, TCE concentrations in this well ranged from less than 0.5 to 5.1 $\mu\text{g/L}$. None of the semivolatile organic compounds on the U.S. Environmental Protection Agency's priority-pollutant list were detected in water from well 1.

Soil gas was sampled at a depth of 3.5 feet below land surface in areas of suspected ground-water contamination. Analyses by gas chromatography indicated the presence of TCE in soils about 230 feet east of well 1 in the area of a former industrial site where solvents were handled. TCE concentrations in the soil gas of this area ranged from 0.2 to 30 $\mu\text{g/L}$. TCE was not detected in soil gas near any of the wells.

Depth to water at the wells ranged from 39 to 49 feet. The regional direction of ground-water

flow is to the west-southwest, which would cause contaminants dissolved in ground water below the former industrial-site area to be transported toward the public-supply wells.

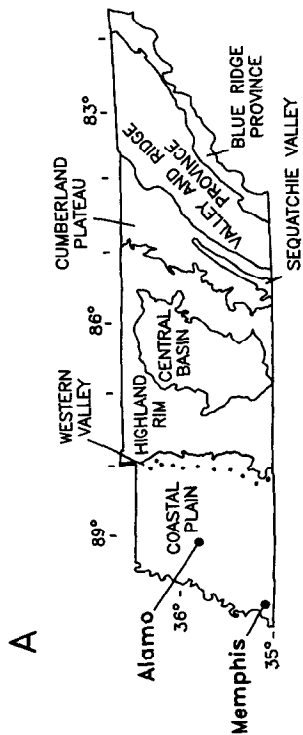
Probable reasons contributing to the lack of TCE detection in soil gas at wells 1 and 2 are the relatively low concentrations of TCE in ground water at the wells and the vertical distance between sampling points and the water table.

INTRODUCTION

The Memphis aquifer is an areally extensive, thick deposit of water-bearing sand that underlies much of western Tennessee. This aquifer is the primary source of water for more than a million residents of the region and the only source of water for residents of Alamo, a small city about 70 miles northeast of Memphis (fig. 1). At Alamo, about 0.3 million gallons of water per day are pumped from four wells screened in this aquifer.

In 1989, the U.S. Geological Survey (USGS), as part of its ongoing study of water quality associated with the major aquifers of western Tennessee, conducted a reconnaissance-level investigation of contamination of the Memphis aquifer at Alamo. The investigation was conducted by the USGS in cooperation with the Tennessee Department of Health and Environment (TDHE), Division of Superfund.

The TDHE, in 1988, found that water from two of Alamo's four wells contained volatile organic compounds (VOC's). Compounds identified



Modified from N.M. Fenneman (1946)

EXPLANATION

- COASTAL PLAIN AND APPROXIMATE EXTENT OF THE MISSISSIPPI EMBAYMENT (From Hosman and others, 1968)
- 4. ACTIVE PUBLIC-SUPPLY WELL AND IDENTIFYING NUMBER

B

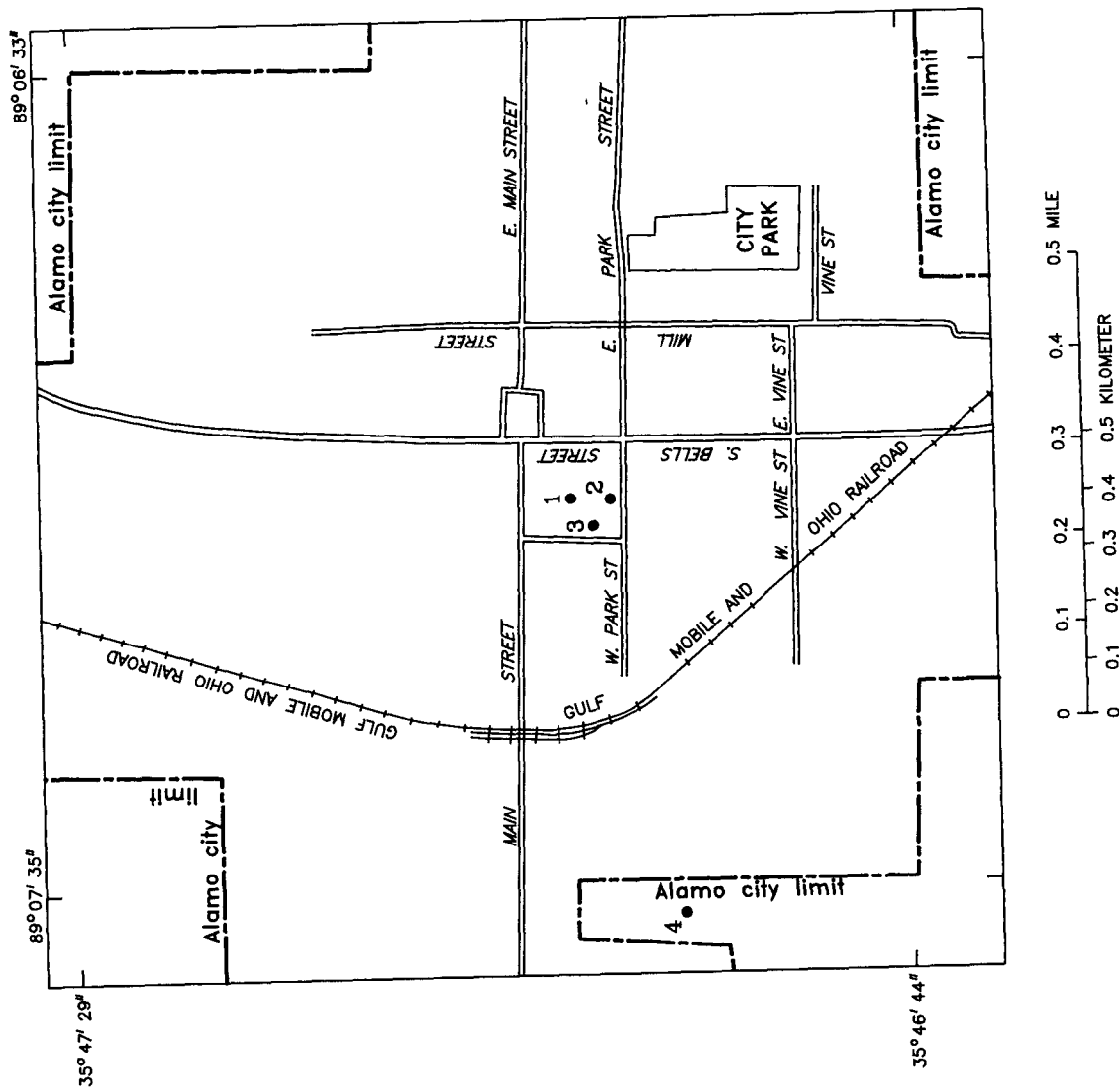


Figure 1.--(A) Tennessee section of the Coastal Plain and Mississippi embayment; and (B) location of active public-supply wells in and near Alamo.

were trichloroethylene (TCE), dichloroethylene, trichloroethane, ethylene chloride, and carbon tetrachloride. TCE was identified in water from well 1 at a concentration of 113 micrograms per liter ($\mu\text{g/L}$), which greatly exceeded the State's maximum contaminant level (MCL) of 5 $\mu\text{g/L}$ in drinking water (Tennessee Department of Health and Environment, 1988). The other compounds were present in smaller concentrations than that of TCE. Use of well 1 was discontinued immediately after the results of the analyses became known.

Purpose and Scope

This report summarizes the results of the reconnaissance investigation conducted in 1989. The purpose of the report is to:

- Describe the general geology and hydrology of the Alamo area;
- Characterize present water quality and document the magnitude of contamination;
- Identify the immediate area(s) affected by ground-water contamination; and
- Evaluate the use of soil-gas analyses as a technique for quickly mapping VOC's in the geologic environment of Alamo.

As a part of this investigation, water samples from four public-supply wells, which were the only available wells in and near the city of Alamo, were analyzed for VOC's. Water from well 1 also was analyzed for semivolatile organic priority pollutants, and water from well 3, was analyzed for common ions.

Soil gas was analyzed at 42 sampling points near the wells for selected VOC's. Soil-gas analysis of the unsaturated zone is a relatively new investigative technique for quickly determining the extent of contamination in the saturated zone. Its use at Alamo was to test this technique in a setting that appeared to offer potential for success, and to evaluate its application to similar studies in other areas.

Description of the Study Area

The study area comprised about 1 mi^2 , which included most of the city of Alamo. The area is characterized by gentle to moderate relief with altitudes ranging from about 350 to 390 feet above sea level. Ephemeral streams provide surface drainage from Alamo to the Middle Fork Forked Deer River and to the South Fork Forked Deer River, about 5 miles north and 7 miles south, respectively. The city's primary well field consists of wells 1, 2, and 3, and is located in a developed section of the city, about 500 feet south of the surface-drainage divide. About 230 feet east of the well field, and within the same city block, is a former industrial site where organic solvents used in the cleaning of electronic components at nearby sites were stored in 55-gallon drums on a porch (Tommy Greene, Mayor of Alamo, oral commun., 1989). The city's well 4 is a supplemental well, located outside the city limits about one-half mile west-southwest of the primary well field.

OVERVIEW OF GEOLOGY AND HYDROLOGY

Alamo is located within the Mississippi embayment of the Coastal Plain physiographic province (fig. 1) (Fenneman, 1946). The Mississippi embayment is a regionally downwarped trough of Paleozoic rocks that is filled with unconsolidated sediments of Mesozoic and Cenozoic age--primarily sand, clay, silt, chalk, gravel, and lignite (Brahana and Mesko, 1988). Near the axis of the Mississippi embayment, these sediments are as much as 3,000 feet thick, but their thickness decreases eastward to about 2,500 to 2,600 feet at Alamo (J. V. Brahana, U.S. Geological Survey, oral commun., 1989).

Regionally, the sediments occur in a sequence of nearly parallel layers that reflect the trough-like shape of the underlying Paleozoic rock. Locally, as in the Alamo area, the sediments occur in discontinuous lenses or beds because of facies changes and post-Cretaceous faulting. Identification and location of these faults commonly are difficult because they are covered by surficial deposits of Quaternary age and because subsurface information is sparse.

Available regional information indicates that the upper 100 feet of sediment underlying Alamo represents either fluvial deposits (W.S. Parks, U.S. Geological Survey, oral commun., 1989) or the Cockfield Formation (Parks and Carmichael, 1990b) (table 1). Data are not available to provide more specific definition. The Cook Mountain Formation, an areally extensive, thick clay deposit, has either a facies change from clay to sand, or is thin or absent at the Alamo well field. The formation is not recognizable on the driller's log of well 3 at Alamo (table 2). Absence of this unit could be the result of a facies change at the time of sediment deposition, or to post-

depositional erosion, or to local faulting of the strata. A driller's log of a well 320-feet deep, 1 mile northwest of Alamo, however, indicates the presence of a clay deposit--which may be the Cook Mountain Formation--at a depth of 120 to 140 feet below land surface.

Underlying the Cook Mountain Formation is the Memphis Sand. It is an areally extensive unit that consists of a thick deposit of sand with clay lenses at various horizons. The Cockfield Formation, Cook Mountain Formation, and Memphis Sand comprise the Claiborne Group.

Table 1.-- *Stratigraphic units underlying Alamo and their hydrologic significance*
[Modified from Parks and Carmichael, 1990b]

System	Series	Group	Stratigraphic unit	Thickness (in feet)	Lithology and hydrologic significance
Quaternary and Tertiary(?)	Pleistocene and Pliocene(?)		Fluvial deposits (terrace deposits)	0-100	Sand, gravel, minor clay and ferruginous sandstone. Thickness varies greatly because of erosional surfaces at top and base. Deposits provide water to farm and domestic wells in rural areas.
Tertiary	Eocene	Claiborne	Cockfield Formation	0-270	Sand, silt, clay, and lignite. Thickness is estimated on the basis of tentative geophysical log correlations. The Cockfield Formation provides water for farm and domestic supplies and some public and industrial supplies.
			?		
			Cook Mountain Formation	40-200	Clay, silt, and sand. The Cook Mountain Formation generally consists of clay and silt, but locally may consist predominately of fine sand. Thickness probably averages about 70 feet. This formation can be confused with clay lenses in the lower part of the Cockfield Formation or upper part of the Memphis Sand. It serves as the upper confining unit for the Memphis Sand.
			?		
			Memphis Sand ("500-foot" sand)	400-890	Sand, silt, clay, and minor lignite. The Memphis Sand consists of a thick body of sand with clay lenses at various horizons. Sand is fine to very coarse. The upper part of the formation commonly contains fine sediments, particularly north of the Hatchie River where drilling to the middle or lower parts of the formation is necessary in order to install large capacity wells. The formation is a major aquifer providing water for most public and industrial supplies in western Tennessee, and the principal aquifer supplying water to the city of Memphis. It is underlain by the Flour Island Formation of the Wilcox Group, which serves as the lower confining unit.

Table 2.--*Driller's formation log of public-supply well 3,
Alamo, Tennessee*

Depth below land surface, in feet	Thickness, in feet	Composition
20	20	Clay - sand
40	20	Fine sand
60	20	Fine sand
80	20	Fine sand
100	20	Medium sand
120	20	Medium sand
140	20	Medium sand
160	20	Coarse sand
180	20	Coarse sand
200	20	Coarse sand

The Cockfield Formation and Memphis Sand are water-bearing units and, where saturated, comprise the Cockfield and Memphis aquifers. The Cook Mountain Formation comprises the Cook Mountain confining unit that separates these aquifers throughout most of the region. At Alamo, the Memphis aquifer is locally unconfined. Static water levels at the Alamo public-supply wells, screened in the Memphis Sand, range from 39 to 49 feet below land surface (table 3). Although extensive water-level data are not available, the configuration of the water table is thought to reflect the topography.

The Memphis aquifer at Alamo is recharged by precipitation that infiltrates through the fluvial deposits or the Cockfield Formation. The direction of shallow ground-water flow is to the west-southwest (Brahana and others, 1986) except near the well field where the flow direction is toward pumped wells as a result of increased horizontal hydraulic gradient caused by the pumping of 0.3 million gallons of water per day. Deeper water moves west-southwest, following the

westerly dip of the Claiborne Group strata through the regionally extensive part of the Cockfield and Memphis aquifers (Brahana and others, 1986).

Data describing the hydraulic characteristics of the aquifer at Alamo are limited to drillers' records and one driller's log (tables 2 and 3). These records indicate that the specific capacities of the wells drilled into the medium-grained sands (well 5) and the coarse-grained sands (well 3) are similar: 7 and 5.1 gallons per minute per foot of drawdown, respectively. The relatively low specific capacities for these two wells indicate that these medium- and coarse-grained sands may occur as discontinuous lenses at the well field.

Water-quality data for the Memphis aquifer at Alamo span a 60-year period (table 4). As revealed by these analyses, water from this part of the aquifer has varied from soft to moderately hard [18 to 66 milligrams per liter (mg/L) as calcium carbonate (CaCO_3)]. Concentrations of dissolved solids have ranged from 44 to 224 mg/L. Iron concentrations at Alamo have ranged from 5 to

Table 3.--Aquifer and well-construction characteristics for public-supply wells at Alamo, Tennessee

[Tm, Memphis Sand; --, no data. Sources: (a), W S. Parks, U.S. Geological Survey, oral commun., 1989; (b), Rodney Wilson, Wilson Drilling Company, oral commun., 1989; (c), altitudes estimated from 7.5-minute topographic quadrangle maps]

Public-supply well number ¹	USGS well number	Water bearing unit (a)	Date drilled (b)	Altitude in feet above sea level (c)	Well depth, below land surface, in feet (b)	Depth cased, below land surface, in feet (b)	Screen length, in feet (b)	Static water level below land surface, in feet (b)	Pumping rate gallon per minute (b)	Specific capacity, gallons per minute per foot of drawdown (b)
1	354705089070501	Tm	1955	349	127	101.8	25	39	350	--
2	354702089070601	Tm	1968 or 1970	351	125.8	--	25	49	150	--
3	354703089070701	Tm	1980	351	213	150	45.7	46	315	5.1
4	354656089073601	Tm	1968	361	140	--	30	--	--	--
5 ²	354652089070601	Tm	1936	359	128.3	97.4	30.9	43	152	7
6 ²	none	Tm	1944	361	125.5	90.7	25	49	200	--

¹See figure 2.

²Abandoned.

2,600 µg/L. In comparison, the median iron concentration for the Memphis aquifer in western Tennessee is 300 µg/L (Parks and Carmichael, 1990a). This value (300 µg/L) corresponds to Tennessee's secondary MCL for iron (Tennessee Department of Health and Environment, 1988).

of ground-water and soil-gas analyses. The ground-water analyses provided limited data on the extent, location, and identity of contaminants in the saturated zone, whereas the soil-gas analyses provided similar information about contaminants in the unsaturated zone.

OCCURRENCE OF VOLATILE AND SEMIVOLATILE ORGANIC COMPOUNDS IN THE MEMPHIS AQUIFER

The extent of contamination and potential for migration of contaminants in the Memphis aquifer at Alamo were evaluated using the results

Ground-Water Analyses

Water samples collected from the four public-supply wells at Alamo, during September 1989, were analyzed for a suite of 36 volatile organic compounds at a detection limit of 0.2 µg/L (table 5). The water sample from well 1 also was

Table 4.--Concentrations of major inorganic constituents and physical properties of ground water from public-supply wells, Alamo, Tennessee

[mg/L, milligrams per liter; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter at 25° Celsius; --, no data. Source of data: well 7, Wells (1933); well 1, Lanphere (1955); well 2, USGS files; well 3, Lowery and others (1986) and USGS file]

Constituent or property	Analytical results for sample from indicated well and year of analysis (in parentheses)				
	Well number 7 (1929 ¹)	Well number 1 (1953 ¹)	Well number 2 (1984)	Well number 3	
				(1984)	(1989)
Silica, dissolved (SiO ₂) (mg/L)	6	21	22	11	22
Iron, dissolved (Fe) (µg/L)	400	80	180	2,600	5
Calcium, dissolved (Ca) (mg/L)	15	17	9.3	4.2	7.9
Magnesium, dissolved (Mg) (mg/L)	2	5.7	3.5	1.7	2.8
Sodium, dissolved (Na) (mg/L)	15	41	29	5.5	29
Potassium, dissolved (K) (mg/L)	15	2.1	.7	.6	.7
Bicarbonate, dissolved (HCO ₃) (mg/L)	54	53	49		
Sulfate, dissolved (SO ₄) (mg/L)	3	17	6	4	8
Chloride, dissolved (Cl) (mg/L)	22	42	26	2.3	16
Nitrate (NO ₃ , as N) (mg/L)	.2	44	20	--	--
Nitrite plus nitrate total (mg/L as N)	--	--	--	--	.90
Dissolved solids, dissolved (mg/L)	87	224	131	44	136
Hardness (mg/L as CaCO ₃)	26	66	38	18	31
Specific conductance, (µS/cm)	--	--	--	77	--
pH, standard units	--	--	--	5.9	5.8
Temperature, in degrees Celsius	--	16.1	17.2	16.5	17

¹Assumed date.

analyzed for 54 semivolatile organic priority pollutants (table 6). Detection limits for the semi-volatile organic compounds ranged from 5 to 30 µg/L. The volatile and semivolatile organic compound analyses were performed at the USGS National Water Quality Laboratory in Arvada, Colo., using gas chromatography and mass spectrometry. A library search of approximately 70,000 compounds was conducted on all water samples for additional organic substances using

the National Institute of Standards and Technology mass spectral library. The chlorinated volatile organic compounds TCE, trichloroethane, 1,1-dichloroethylene, and tetrachloroethylene were detected in water samples from both wells 1 and 2. Carbon tetrachloride, 1,1-dichloroethane, 1,2-transdichloroethylene, and chloroform also were detected in water from well 1. Concentrations in water samples from wells 1 and 2 were 45 and 0.7 µg/L TCE; 32 and 0.9 µg/L 1,1-dichloroethylene;

Table 5.--*Concentrations of volatile organic compounds in ground-water samples collected in September 1989, Alamo, Tennessee*

[Concentrations in micrograms per liter, as total recoverable; <, concentration is less than the detection limit for the compound]

Compound name	Concentration in sample from indicated well (in micrograms per liter)			
	Well number 1	Well number 2	Well number 3	Well number 4
1,1-Dichloroethylene	32	0.9	<0.2	<0.2
Tetrachloroethylene	1.2	< .2	< .2	< .2
1,1,1-Trichloroethane	38	1.3	< .2	< .2
Trichloroethylene (TCE)	45	.7	< .2	< .2
Carbon tetrachloride	1	< .2	< .2	< .2
Chloroform	.2	< .2	< .2	< .2
1,1-Dichloroethane	.2	< .2	< .2	< .2
1,2-trans-Dichloroethylene	.2	< .2	< .2	< .2
Benzene	< .2	< .2	< .2	< .2
Bromoethane	< .2	< .2	< .2	< .2
Chlorobenzene	< .2	< .2	< .2	< .2
Chloroethane	< .2	< .2	< .2	< .2
2-Chloroethylvinyl ether	< .2	< .2	< .2	< .2
Chloromethane	< .2	< .2	< .2	< .2
1,3-cis-Dichloropropene	< .2	< .2	< .2	< .2
Dibromochloromethane	< .2	< .2	< .2	< .2
1,2-Dibromoethane; (or EDB, ethylenedibromide)	< .2	< .2	< .2	< .2
1,2-Dichlorobenzene	< .2	< .2	< .2	< .2
1,3-Dichlorobenzene	< .2	< .2	< .2	< .2
1,4-Dichlorobenzene	< .2	< .2	< .2	< .2
Dichlorobromomethane	< .2	< .2	< .2	< .2
Dichlorodifluoromethane	< .2	< .2	< .2	< .2
1,2-Dichloroethane	< .3	< .2	< .2	< .2
Dichloromethane	< .2	< .2	< .2	< .2
1,2-Dichloropropane	< .2	< .2	< .2	< .2
1,3-Dichloropropene	< .2	< .2	< .2	< .2
Ethenylbenzene	< .2	< .2	< .2	< .2
Ethylbenzene	< .2	< .2	< .2	< .2
1,1,2,2-Tetrachloroethane	< .2	< .2	< .2	< .2
Toluene	< .2	< .2	< .2	< .2
1,3-trans-Dichloropropene	< .2	< .2	< .2	< .2
Tribromoethane	< .2	< .2	< .2	< .2
1,1,2-Trichloroethane	< .2	< .2	< .2	< .2
Trichlorofluoromethane	< .2	< .2	< .2	< .2
Vinyl chloride	< .2	< .2	< .2	< .2
Xylenes, mixed	< .2	< .2	< .2	< .2

Table 6.--Concentrations of semivolatile organic compounds in a water sample collected from well 1 in September 1989, Alamo, Tennessee

[Concentrations in micrograms per liter; <, concentration is less than the detection limit for the compound; gas chromatography and mass spectrometry analysis of semivolatile compounds, base/neutral plus acid-extractable, total recoverable]

Compound name	Concentration	Compound name	Concentration
Acenaphthylene	< 5	Benzo (a) anthracene	<10
Acenaphthene	< 5	1,2-Dichlorobenzene	< 5
Anthracene	< 5	1,2,4-Trichlorobenzene	< 5
Benzo (b) fluoranthene	<10	Dibenzo (a,h) anthracene	<10
Benzo (k) fluoranthene	<10	1,3-Dichlorobenzene	< 5
Benzo (a) pyrene	<10	1,4-Dichlorobenzene	< 5
bis (2-Chloroethyl) ether	< 5	2-Chloronaphthalene	< 5
bis (2-Chloroethoxy) methane	< 5	2-Chlorophenol	< 5
bis (2-Chloroisopropyl) ether	< 5	2- Nitrophenol	< 5
Butyl benzyl phthalate	< 5	Di-n-octylphthalate	<10
Chrysene	<10	2,4-Dichlorophenol	< 5
Diethyl phthalate	< 5	2,4-Dimethylphenol	< 5
Dimethyl phthalate	< 5	2,4-Dinitrotoluene	< 5
Fluoranthene	< 5	2,4-Dinitrophenol	<20
Fluorene	< 5	2,4,6-Trichlorophenol	<20
Hexachlorocyclopentadiene	< 5	2,6-Dinitrotoluene	< 5
Hexachloroethane	< 5	4-Bromophenyl phenyl ether	< 5
Indeno (1,2,3-cd) pyrene	<10	4-Chlorophenyl phenyl ether	< 5
Isophorone	< 5	4-Nitrophenol	<30
n-Nitrosodi-n-propylamine	< 5	2-Methyl-4,6-dinitrophenol	<30
n-Nitrosodiphenylamine	< 5	Phenol	< 5
n-Nitrosodimethylamine	< 5	Naphthalene	< 5
Nitrobenzene	< 5	Pentachlorophenol	<30
4-Chloro-3-methylphenol	<30	bis (2-Ethylhexyl) phthalate	< 5
Phenanthrene	< 5	Di-n-butyl phthalate	< 5
Pyrene	< 5	Hexachlorobenzene	< 5
Benzo (g,h,i) perylene	<10	Hexachlorobutadiene	< 5

and, 38 and 1.3 µg/L 1,1,1-trichloroethane, respectively. Tennessee's maximum contaminant level for TCE in drinking water is 5 µg/L; its recommended maximum contaminant level for dichloroethylene in drinking water is 7 µg/L and for trichloroethane, 200 µg/L (Tennessee Department of Health and Environment, 1988). Toluene and benzene compounds, commonly associated with petroleum products, were not

detected in water from any of the wells. Analysis of the water sample from well 1 indicated that none of the semivolatile organic compounds on the U.S. Environmental Protection Agency's priority-pollutants list were present at or above the detection limits.

Water samples were collected from the four public-supply wells by the TDHE at monthly

intervals from July 1988 to July 1989. These samples were analyzed for VOC's by a commercial laboratory (Tennessee Department of Health and Environment, written commun., 1989). TCE, dichloroethylene, trichloroethane, and carbon tetrachloride were detected in the samples from wells 1 and 2. The detection limit was 0.5 $\mu\text{g/L}$. Concentrations of TCE in water from well 1 ranged from 40 $\mu\text{g/L}$ (July 1989) to 113 $\mu\text{g/L}$ (September 1988). Concentrations of TCE in water samples collected at well 2 ranged from less than 0.5 $\mu\text{g/L}$ (July 1989) to 5.1 $\mu\text{g/L}$ (October 1988). Although these data imply a continuing decrease in concentrations with time, it is difficult to interpret these changes as actual decreases in concentration in the aquifer. The chemical quality of ground water at the wells can vary from one sampling period to another for many reasons. Among those reasons are discontinuous pumping patterns that continuously alter flow patterns near the wells, and differences in the chemical composition of water and rate of recharge from the surrounding area.

At the time of the USGS investigation, only the two shallowest wells, well 1 (127 feet) and 2 (125.8 feet), yielded water with detectable concentrations of TCE. VOC's were not detected in the water from well 3, the deepest well (213 feet), or from well 4, the well farthest from the industrial site where solvents were handled. Thus, only the upper part of the aquifer, in an area extending from a possible source area west-southwesterly to include wells 1 and 2, but not as far as well 4, appears to have been impaired by VOC's.

Soil-Gas Analyses

Soil-gas analyses were used in an effort to detect VOC's above the ground water because VOC's readily partition at the water table and diffuse through soil gas in a predominantly vertical direction (Marrin and Thompson, 1987). TCE, a member of the VOC family, has an air/water partition coefficient of 0.385 (dimensionless) and readily partitions out of the ground water to diffuse through the soil gas. Air/water partitioning and gaseous diffusion are probably the dominant mechanisms involved in transporting TCE from the ground water through the shallow soil gas.

Soil gas was collected at 42 sampling points and analyzed for VOC's (fig. 2). These analyses provided an initial estimate of the direction, areal extent, and chemical composition of the contaminant plume. The sampling points were located at the former industrial site, hydraulically downgradient of an underground gasoline-storage tank, adjacent to a vehicle maintenance building, and near each well. When a compound was detected at a sampling site, additional sampling sites were selected in a pattern that extended radially outward until no VOC's were detected.

Soil-gas samples were collected and analyzed in the field using procedures described by Brock (1990). First, a 1 1/2-inch-diameter hole was drilled with an electric drill to a depth of 3.5 feet. Then a 1/4-inch stainless-steel probe was inserted into the hole. Modeling clay was used to assure a good seal around the probe at land surface. Soil gas was withdrawn using a peristaltic pump for approximately 2 minutes to establish an equilibrium within the probe. A sample was then withdrawn from a port in the probe using a glass syringe and injected into the field gas chromatograph for analysis. The analyses were done using a Photovac 10S50 portable gas chromatograph equipped with an isothermal capillary column and a photoionization detector.

The gas chromatograph was calibrated to known concentrations of the compounds cis-dichloroethylene, trans-dichloroethylene, benzene, toluene, trichloroethylene, and carbon tetrachloride. Compounds from the soil-gas samples were identified in the field by comparing retention times of the sample with retention times of the standard compounds. Standards were run at the beginning and end of each day and after approximately every 10 samples. Additionally, an instrument blank was run at the start of each day and probe blanks were run throughout the day.

TCE was detected in 13 of the 42 soil-gas samples. Concentrations ranged from 0.2 to 30 $\mu\text{g/L}$ (fig. 2). These 13 samples were collected at or near the former industrial site east of well 1. TCE was not detected in any of the soil-gas samples collected near the wells. Samples were not collected from soil beneath the adjacent pavement. None of the other five compounds used to calibrate the field gas chromatograph were detected in the analyses. The small areal distribution of sites where TCE was detected indicates that

Figure 2.--Sketch showing location of the public-supply wells and soil-gas sampling sites.

this area probably is a source area where organic solvents containing TCE percolated into the ground.

Potential Migration of Contaminants

The limited scope of the investigation did not provide conclusive evidence that contaminants have migrated from the source area to the well field. The dates and quantity or quantities of TCE that entered the ground, initial concentration in ground water, rate of dilution, rate of transport, and initial concentrations of TCE in the well water are unknown factors. However, the hydrogeology of the study area and the physical and chemical characteristics of TCE indicate that TCE and other VOC's at the contaminated area could have readily migrated downward with recharge. TCE is characterized by high water solubility (1,100 mg/L); high vapor pressure (60 millimeters of mercury); relatively low molecular weight (131.5); and a specific gravity of 1.46 (Verschueren, 1983). These chemical and physical properties indicate TCE is highly mobile in ground-water systems (Smith and Dragun, 1984) and could have migrated downward through the unsaturated zone to the water-table aquifer. Once dissolved in the ground water, the VOC's could have moved downgradient toward the wells being pumped.

Hydrogeologic factors at the site that favor transport of VOC's through the shallow subsurface include highly permeable sands, shallow depth to water (table 3), and lack of a continuous impermeable unit to confine and protect the aquifer. The west-southwesterly direction of ground-water flow would likely cause VOC's to move in a plume from the probable source area toward the wells to the west-southwest.

Several possible reasons can be advanced to explain why a TCE plume was not evident in the soil gas beyond the probable source area. They include:

- (a) A large percentage of the TCE and other VOC's may be sorbed to particles in the unsaturated zone, and the largest concentration of VOC's may reside in the upper part of the unsaturated zone. Additionally, vapor concentrations emanating from the upper part of the unsaturated zone

undergo less diminution by diffusion than those originating from near water-table depth.

- (b) Upon entering the ground-water reservoir, the concentration of contaminants is further diminished by dilution in water and may be attenuated by additional sorption to the aquifer skeleton (Thompson and Marrin, 1987).
- (c) Rain fell the day before sampling was done. Infiltrating water may have dissolved TCE in soil gas near the wells to concentrations below the level of detection. Soil-gas responses have been observed in the field to be reduced immediately following rainfall (Crockett and Taddeo, 1988).
- (d) The wells may have been drilled through relatively thin clay lenses or layers that were not recorded in the driller's log (table 2), based on samples taken at intervals of 20 feet. If present, clay layers, even though not thick, could provide a partial barrier to the upward diffusion of gases. VOC concentrations in soil gas above any diffusion-limiting layer will be lower than concentrations below (Marrin and Kerfoot, 1988).

EVALUATION OF SOIL-GAS APPROACH

Soil-gas analyses were extremely useful in locating a relatively small area east of well 1 where soils had been contaminated with TCE and other VOC's. That area probably represents a source area where organic solvents containing TCE and perhaps others VOC's infiltrated into the ground. The technique, however, did not define a plume extending outward from that area. As noted previously, there are several possible explanations as to why the plume could not be mapped using this technique. The technique has been used to successfully define VOC plumes elsewhere. In a test of the method at Jackson, Tennessee, for example, a VOC plume in a sand aquifer was successfully delineated by soil-gas analyses (Lee, 1991). One of the more significant hydrologic differences between the Jackson and Alamo sites was depth to water. At the Jackson site, depth to water

was 2 to 6 feet below land surface. If equipment had been available to insert the probes to greater depth at the Alamo study area, it may have been possible to map more of the plume using soil-gas analyses. Also, VOC concentrations at the Jackson site were several orders of magnitude higher than those at Alamo. Detectable VOC concentrations at Jackson ranged from 5 mg/L to greater than 10,000 mg/L (5 parts per million to greater than 10,000 parts per million), as compared to 0.2 to 30 µg/L at Alamo.

Results of this study indicate that soil-gas analysis techniques are useful in locating VOC's in the shallow unsaturated zone, even in relatively low concentrations. In ground-water systems, such as that at Alamo, where the thickness of the unsaturated zone is about 40 feet, soil-gas analyses may be of limited value in mapping VOC's in low concentrations in ground water unless soil-gas probes are inserted to depths near the water table.

SUMMARY

Samples of ground water and soil gas were analyzed to study the occurrence of VOC's in the Memphis aquifer at Alamo, western Tennessee, in 1989. Four wells screened in the Memphis aquifer provide residents of Alamo with 0.3 million gallons of water per day. TCE was present in water from two of the four wells. Concentrations were 0.7 µg/L in water from well 2 and 45 µg/L in water from well 1. Tennessee's MCL for TCE in drinking water is 5 µg/L. Dichloroethylene also was detected in water from well 1 at a concentration of 32 µg/L, exceeding the State's recommended maximum contaminant level of 7 µg/L. During a TDHE investigation in 1988-89, TCE concentrations in water from well 1 ranged from 40 to 113 µg/L. VOC's were not detected in the samples from wells 3 (the deepest of the wells, 213 feet) and 4 (approximately one-half mile west-

southwest of wells 1, 2, and 3). Semivolatile organic compounds were not present at or above the detection limits in the sample from well 1.

TCE was detected in 13 of the 42 soil-gas samples. The 13 samples containing TCE are from an area approximately 230 feet east of well 1. This area is a former industrial site where solvents were handled. Concentrations of TCE in the soil gas ranged from 0.2 µg/L (the lower detection limit) to 30 µg/L. Organic solvents percolating into the ground in this area may have been transported through the underlying sands and reached the water table. Chemicals dissolved in the ground water would be transported in the direction of the prevailing hydraulic gradient, which would cause them to migrate toward the city's wells. However, neither TCE nor other VOC's were detected in the soil gas near any of the public-supply wells.

Based on these data, the areal extent of aquifer affected by VOC's in the ground water appears to be limited. It probably extends from the former industrial site to some point beyond wells 1 and 2, but not as far as well 4. The limited data indicate that only the water in the upper part of the aquifer has been impaired.

Soil-gas analyses were useful in quickly identifying a probable source area where organic solvents containing TCE and perhaps other VOC's infiltrated into the ground. The technique, however, did not identify a plume extending outward from that area. Although there are several possible explanations as to why the plume could not be mapped using this technique, the thickness of the unsaturated zone was probably a major factor. It may have been possible to map the plume if the soil-gas probes, which were inserted to a depth of only 3.5 feet, had been inserted to depths closer to that of the water table (about 39 to 49 feet) or if concentrations of VOC's in the ground water had been greater than they were.

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